

SPECIMEN HEAT FLUXES FOR BENCH-SCALE HEAT RELEASE RATE TESTING

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ABSTRACT

When a specimen is tested for its heat release rate (HRR) behavior using a bench-scale test such as ISO 5660 or equivalent, one very important test condition is not pre-standardized and must be set: the heat flux to be imposed on the specimen by the heater. The heat flux cannot be legitimately standardized, since the value appropriately to be used will differ according to purpose or application. The present paper sets forth the considerations which should govern the correct choice of heat flux. A discussion is given of minimum ignitability level; statistical variability at low heat fluxes; the ranges of heat fluxes associated with small actual ignition sources; the heat fluxes associated with fires away from the ignition source, all the way up to fully-involved room fires; the application of the product; and the needs associated with mathematical modeling of room fires. Correlational approaches are also illustrated and contrasted to physics-based ones. Finally, the empirical nature of the present situation is emphasized. Judged from first principles, it would appear that successful prediction of room fire results from bench-scale test data would require both the testing at a large number of different heat fluxes and the use of algorithms to permit time-dependent interpolation. Such algorithms have been proposed; however, some very successful predictions are noted with much simpler techniques.

Keywords: Cone Calorimeter, heat release rate, radiant heating, room/corner tests, upholstered furniture, wall fires.

INTRODUCTION

Heat release rate (HRR) testing is intended to measure a *property* of the test material or product. In terms of thermophysical and thermochemical behavior, it is understood that the property may really be a 'quasi-property,' that is, it is not truly independent of test conditions. Nonetheless, the design of a good HRR apparatus [1] is predicated on keeping the apparatus-dependent aspects to a minimum in order to capture the essential property of the material. The emphasis on obtaining measurements which are genuinely properties of the materials is motivated by the use of the data. Sometimes it is sufficient to use data solely for simple rank-ordering of performance. In most cases, however, bench-scale HRR data are taken so that larger-scale fire performance might be predicted. This prediction can take the form of a simple correlation or of a detailed mathematical model. In each of those cases what is desired is the response of a unit surface element of the material to a known external heat flux. This characteristic can be considered the *true response*, while any other factors which are present in the bench-scale test apparatus but not in the real-scale fire are *apparatus-dependent errors*.

From this discussion it is immediately evident that the one unconstrained variable in bench-scale HRR testing which is a genuine parameter of the test and not an apparatus error is the *irradiance* or *imposed heat flux* on the specimen. In general, of course, irradiance and heat flux are not synonymous, since a convective flux may also be present. For most bench-scale HRR test applications, however, the test is designed so that the convective portion of the heat flux is very small and can

INTERFLAM '93

often be neglected. But, what heat flux to impose? A search of the literature will reveal that values anywhere from 20 to 100 kW·m⁻² have been used—clearly the selection needs to be made much more specific for any concrete testing project.

The question of what heat flux to use turns out to be not at all simple. Furthermore, it is an area where there has not yet been much consensus within the profession as to proper procedures. Thus, in this paper we will examine the state of current knowledge and assemble as much evidence as possible that may be helpful in providing guidance in testing.

RANGE OF IRRADIANCES FEASIBLE IN BENCH-SCALE HRR APPARATUSES

(a) Lower limits

An obvious limitation to the heat flux to be imposed on the bench-scale test specimen is that it should be within the physical capabilities of the test apparatus being used. At the lower end, HRR apparatus using electrical heaters can go down to a flux of zero. Gas-fired HRR apparatuses had a very distinct lower limit governed by the stability of the flame upon the heating panels. This used to be highly specific to the test hardware, but a value of *ca.* 20 kW·m⁻² was typical. This lower limit is nowadays irrelevant since gas-fired HRR apparatuses are no longer in common use.

Another lower limit stems from measurement errors in calibration. Robertson [2],[3] has considered the errors in the heat flux meters normally used for calibrating HRR apparatuses. He found that for heat fluxes ≤ 10 kW·m⁻² accurate calibrations are difficult. At such low flux levels the convective component is no longer a small, negligible contribution to the total heat flux. This heat flux is apparatus-dependent since convective flows are directly governed both by geometric size and edge conditions and by the specimen's own surface temperature and even its lateral distribution. Thus, one cannot *impose* a prescribed convective flux the way that a prescribed irradiance can be imposed.

(b) Upper limits

The older generation of HRR apparatus typically were designed to have a maximum irradiance of around 70 kW·m⁻² possible [1]. The actual design limit was often unrealistic. Thus, the OSU apparatus [4], as an example, was intended to have an upper limit of 100 kW·m⁻² but users had difficulty reliably achieving more than *ca.* 50 kW·m⁻². For current use, the Cone Calorimeter (ISO 5660 [5], ASTM E 1354 [6]) has been designed for 100 kW·m⁻² not only as the specified upper limit in the standards, but also as a value which is reliably achievable. This represents the upper limit available to most laboratories. For some specialized studies, unusual HRR apparatuses have been constructed that can reach an irradiance of 250 kW·m⁻²[7]; such capabilities are generally not associated with civilian-sector work.

With the above current-day capabilities in mind, we will examine later whether technical needs imply that they are sufficient.

HEAT FLUXES FOUND IN FIRES

Certainly a major consideration in the selection of the test irradiance must come from a knowledge of heat fluxes associated with real fires. In theory, this could range from zero to an upper value which would be σT^4 , where for the temperature T the maximum flame temperature it taken. The maximum flame temperature for most organic fuels is approximately 2300 K [8]. Since the Stefan-Boltzmann constant σ is $5.67 \cdot 10^{-11}$ kW·m⁻²·K⁻⁴, this would suggest an irradiance of some 1500 kW·m⁻². This fundamental maximum value is, of course, nearly 10× the maximum that is found in building fires types that are of normal relevance.

Thus, it is evident that the theoretical bounds to possible heat fluxes do not offer any guidance for testing. Instead, it will be necessary to look into experimental data on heat fluxes found in actual building fires. We will divide this into several types of building fires to be examined.

(a) Heat fluxes in the vicinity of ignition sources

SMALL BURNERS

First, we must be clear by what is meant by 'ignition source.' The innate definition of the term does not have limits—a burning building can be the ignition source to its neighboring building, as can a fire bomb. For discussion here, however, ignition sources will be limited to those that are small with respect to a fully-developed room fire. Since the latter will be in the range of > 1 MW, the range of fires considered to be ignition sources will be taken as $< ca. 300$ kW.

Table 1 Peak heat fluxes measured for small burner ignition sources

Burner type	Fuel	Power ^b (kW)	Location	Peak heat flux (kWm ⁻²)
Gas flame 1 ^a	butane	0.082	^c	35 - 40
Gas flame 2 ^a	"	0.291	^c	31 - 39
Gas flame 3 ^a	"	0.636	^c	20 - 40
Tube burner	propane	2.8	45° upward	34
"	"	14.	"	36
"	"	21.	"	38
Tube burner	butane	3.6	45° upward	36
"	"	18.	"	36
"	"	27.	"	36
Tube burner	butane	3.6	70° downward	^d
"	"	18.	"	40 - 44
"	"	27.	"	50 - 52

^a As defined according to BS 5852.
^b Based on net heat of combustion.
^c Similar results seen for horizontal orientation and for 45° upward.
^d Not sustained.

A few years ago, a study at NIST examined various ignition sources, ranging from 5 W to over 300 kW [9]. The sources included both realistic igniting objects (cigarettes, matches, burning paper lunch bags, etc.) and schematic ones (small gas burners and wood cribs). It was found that, as the power output of the ignition source increased, the peak heat flux generally did *not* increase. Instead, only the area covered by the peak heat flux progressively increased. For flames ranging from a 0.3 kW Bunsen-type burner to a 50 kW wastebasket, the peak fluxes were remarkably constant at 30 - 40

INTERFLAM '93

$\text{kW}\cdot\text{m}^{-2}$. Only a methenamine pill was significantly outside this range, a peak heat flux of only $4 \text{ kW}\cdot\text{m}^{-2}$ being seen for it. Quintiere examined another set of experimental data and found a range of $20 - 50 \text{ kW}\cdot\text{m}^{-2}$ [10]. Similar conclusions can be seen from the compilation of Paul and Christian [11].

To illustrate this constancy, Table 1 compiles data from several sources [12],[13],[14] on small burner ignition sources. Despite a wide variation in burner power levels, peak irradiance values are all clustered around $35 \text{ kW}\cdot\text{m}^{-2}$.

We do find some data from impinging-type sources that are practical for use in fire tests. For instance, a 'T-head' burner was developed for igniting upholstered furniture. It consists of a tube with numerous small holes, thus discharging at a significantly higher velocity than would be the case of a large open-top burner. Ohlemiller and Villa [15] measured heat fluxes as high as $70 \text{ kW}\cdot\text{m}^{-2}$ in the impinging region of this burner's flame. In a parallel study using several different configurations of impinging flames from multi-hole propane and butane burners [16] more typical fluxes of $50 \text{ kW}\cdot\text{m}^{-2}$ were seen. In another study on various commercial burners and plumber's blow torches, a maximum impinging-zone heat flux of $140 - 150 \text{ kW}\cdot\text{m}^{-2}$ was seen [17]. Some additional details are discussed in [18]. In general, situations involving the impinging-flow geometry are uncommon and specialized. When encountered, generalizations may not be sufficient and specific data gathering may be necessary.

LARGER BURNERS

Data are also available for much larger burners. A study from the Technical Research Center of Finland laboratory [19] gives results for gas burners of 40, 100, 160, 230, and 300 kW power output levels, with the test burners having three different face sizes. From that study it is seen that for the more typical face sizes ($0.17 \text{ m} \times 0.17 \text{ m}$ to $0.30 \text{ m} \times 0.30 \text{ m}$) the peak heat flux to the wall adjacent to the burner is dependent much more on the face size than on the burner output level. A peak value of around $40 \text{ kW}\cdot\text{m}^{-2}$ was seen with the smaller size and 65 to $80 \text{ kW}\cdot\text{m}^{-2}$ with the larger face size. For an unusually-large face size of $0.50 \text{ m} \times 0.50 \text{ m}$, the peak heat flux was seen to be strongly related to the burner output level; such a face size, however, is not used in normal fire testing. Published details are also available for a 50 kW burner [9] used at NIST in furniture testing.

The main point to be observed about the burner fluxes is that (excluding burners with unusually large face dimensions) the peak fluxes are almost independent of burner power output, but the wall area behind the burner subjected to a given flux level is nearly linearly proportional to the burner output level. The latter point is illustrated in Figure 1. A linear relationship is adequate to represent both the small power data from [14] and the 40 to 300 kW sources of [19]. For the latter, area contours identical to the $\geq 20 \text{ kW}\cdot\text{m}^{-2}$ regions were arbitrarily assigned; as a result there is a (slight) systematic mismatch between the two data sets.

SOLID-FUEL IGNITION SOURCES

Very roughly, it can be estimated that the heat flux to *adjacent* objects from a small wood crib or other solid-fuel ignition source is in the same 30 to $40 \text{ kW}\cdot\text{m}^{-2}$ range as for gas burners. The picture is more complicated, however, for the heat flux from these sources to the object *underneath*. There are heat flux data measured from wood crib sources [20]. These measurements show small regions where heat fluxes in the vicinity of $90 \text{ kW}\cdot\text{m}^{-2}$ can be found underneath the burning crib. Unlike other sources, where we consider only radiative and convective heating from gases, in this case the high heat fluxes originate due to direct conductive heating from a hot, glowing body. Such high values are, in fact, consistent with the glowing char temperatures. The actual ignition process from such a source has not been characterized, however, since the heat transfer is definitely not 1-dimensional.

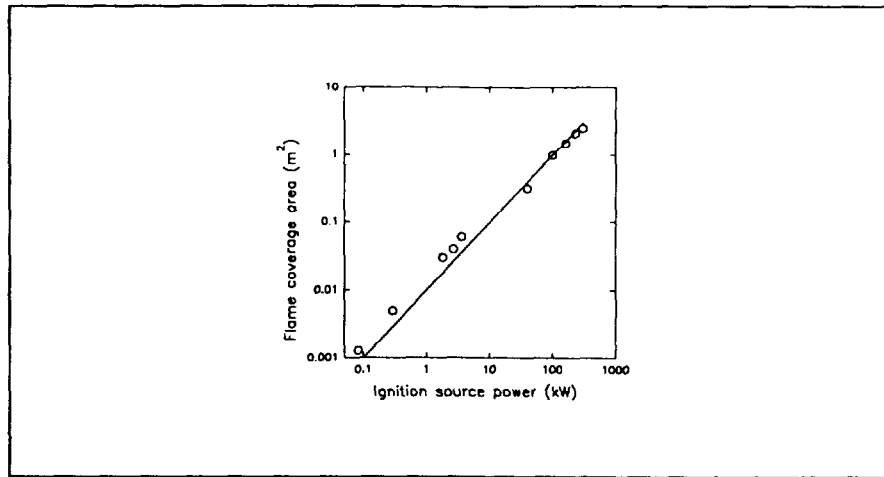


Figure 1 Flame area as a function of ignition source power

For most other solid-fuel ignition sources, localized very high heat fluxes are not found. For instance, Paul and Christian [21] examined the peak heat fluxes found underneath burning balls of crumpled newspaper and underneath wire baskets holding various amounts of shredded paper. The peak heat flux seen in this series of tests was $24 \text{ kW}\cdot\text{m}^{-2}$, with most experiments indicating substantially lower peaks, down to $7 \text{ kW}\cdot\text{m}^{-2}$. Another type of solid-fuel source is the 100 g paper cushion stuffed with newspaper used by the German railroads [22]. Döring and co-workers [23] found a maximum of $35 \text{ kW}\cdot\text{m}^{-2}$ underneath the standard paper cushion. Variants of differing types showed flux peaks of 28 to $47 \text{ kW}\cdot\text{m}^{-2}$. There are some findings contrary to the above, however. Ohlemiller and Villa [15] found substantially higher heat fluxes associated with the newspaper-filled wire basket formerly used as a furniture ignition source by the State of California.

(b) Heat fluxes in preflashover room fires

Heat fluxes occurring in preflashover room fires will vary widely. Away from the initial source of fire there will be essentially no heating at all. Near a small initial fire source, heat fluxes of the sort described in the preceding section will be seen. With increasing fire spread and involvement, a hot gas layer will build up below the ceiling. The heat fluxes will be significantly hotter within this layer than in lower spaces. Söderbom [24] found values typically $< 45 \text{ kW}\cdot\text{m}^{-2}$ at the center of the ceiling during preflashover fires. The value at the floor level is, of course, always $< 20 \text{ kW}\cdot\text{m}^{-2}$ prior to flashover, since attaining $20 \text{ kW}\cdot\text{m}^{-2}$ at floor level is one definition of flashover [25]. Combustion at floor level, however, is not generally where the attention is focused.

(c) Heat fluxes on burning walls

Heat fluxes from burning items of larger types have, in general, not been studied in enough detail to be systematically known. The notable exception is for upward flame spread on vertical surfaces. For this configuration, a number of studies have explored the heat fluxes from the flame to the yet-unignited portion of the surface. Hasemi studied this problem in detail [26] and provided correlations. For his experiments, peak values of $ca. 25 \text{ kW}\cdot\text{m}^{-2}$ were seen for the region downstream of the

INTERFLAM '93

ignited area, but before the tip of the flames; beyond the flame tip, fluxes were no longer constant, but dropping off further downstream. Additional similar data have also been presented in a summary form [27]. Recent work by Kulkarni and co-workers has enlarged the diversity of material types to have been studied [28]. The value of $25 \text{ kW}\cdot\text{m}^{-2}$ is seen from these more extensive studies to be the lower bound of where data are clustered—most of the data are in the interval from 25 to $45 \text{ kW}\cdot\text{m}^{-2}$. Thus, a value of $35 \text{ kW}\cdot\text{m}^{-2}$ might better capture the mean behavior. (Note that insights are not yet available to explain why some materials are at the higher end while others at the lower end of this range.)

A $35 \text{ kW}\cdot\text{m}^{-2}$ (or, alternatively, a range of $25 - 45 \text{ kW}\cdot\text{m}^{-2}$) heat flux, then, can be used to characterize the peak level of heating to a vertical surface element from its own upstream flame, just prior to its ignition. This value will need to be increased if the material is so situated as to be in a hot gas layer that is accumulating in the upper reaches of the room. Apart from the data of Söderbom, discussed in the previous section, this additional heating has not been studied in detail.

(d) Heat fluxes in post-flashover room fires

The maximum temperatures actually seen in post-flashover room fires are *ca.* 1100°C . A perfect black-body radiator at that temperature would produce heat fluxes of approximately $200 \text{ kW}\cdot\text{m}^{-2}$. Actual heat fluxes measured in post-flashover room fires can come close to this value, but are usually somewhat lower. For instance, examining the extensive room burn data of Fang [29], one finds the following ranges of experimental results:

	Heat flux ($\text{kW}\cdot\text{m}^{-2}$)		
	Ceiling	Walls	Floor
Maximum	106 - 176	116 - 229	119 - 143
Average	68 - 147	91 - 194	—

One might reasonably conclude that a heat flux of *ca.* $150 \text{ kW}\cdot\text{m}^{-2}$ would be needed to properly represent the environment of the post-flashover room fire. Such a capability is, of course, as discussed above, outside of the range of what is feasible with most of the current-day instruments.

Interestingly, the inability to realistically create the heat fluxes of the post-flashover fire has not been seen to be a problem in fire testing. Often, the situation is avoided in its entirety by assuming that the maximum burning rate will occur within the room that is consistent with the available oxygen supply [30]. Nonetheless, if for more detailed fire modeling the HRR of individual items in the post-flashover fire would be required, such high heat flux values would be required.

(e) Heat fluxes to the building facade from a window fire plume

This specialized problem is receiving more attention these days as fire performance issues for facades are investigated in greater detail. Older studies have primarily measured temperature distributions only, from which some workers tried to compute heat fluxes [31]. An early series of measurements was reported by the Fire Research Station in England [32]. For a variety of wood crib fires, the heat flux measurements to the facade, above the opening of the burn room window, ranged from about 12 to $40 \text{ kW}\cdot\text{m}^{-2}$. More detailed measurements were reported by Ondrus, at Lund University [33]. Ondrus reports peak values of *ca.* $145 \text{ kW}\cdot\text{m}^{-2}$ at about 0.8 m above the top of the window. This drops to $40 \text{ kW}\cdot\text{m}^{-2}$ at a height of 3.3 m above the window top. In a more recent study at NRC in Canada where wood cribs were also used [34], peak heat fluxes of $80 \text{ kW}\cdot\text{m}^{-2}$ at 0.25 m above the

top of a square-shape window were measured, while $115 \text{ kW}\cdot\text{m}^{-2}$ was recorded with a tall, narrow window. In the same NRC study, propane burner fires were able to cause heat fluxes of over $200 \text{ kW}\cdot\text{m}^{-2}$; such extreme heat fluxes, however, require both very large fires (over 10 MW) and very large window openings. Fires under 6 MW did not create facade heat fluxes over $50 \text{ kW}\cdot\text{m}^{-2}$ at a height of 0.5 m above window top.

The information about heat fluxes to facades presently available does not seem entirely adequate for design purposes. Nonetheless, it can be conjectured that a heat flux of $50 \text{ kW}\cdot\text{m}^{-2}$ may be a reasonable condition for many applications. Values much greater than this can be seen to be created, but this appears to require somewhat specialized fire conditions. The fluxes discussed here have been total heat fluxes in all cases. Unlike inside compartment fires, however, velocities tend to be fairly high, thus the convective component can be roughly of the same magnitude as the radiative. For application to HRR testing, this radiative/convective split can be disregarded and guidance taken from the total heat flux value as being the value to be impressed during test.

THE DEPENDENCE OF HRR ON THE HEAT FLUX

Under this heading, we will examine two concerns: (1) the linearity (or lack thereof) for the heat flux vs. HRR relationship; and (2) testing problems seen at the low end of the scale, near the level of critical irradiance for ignition.

With regards to linearity, the following very broad generalization can be made: for many products, over a substantial heat flux range, the HRR is linearly proportional to the heat flux. This generalization, however, will be seen to have only limited utility, since it is rarely known *a priori* whether or not it will be obeyed. Furthermore, there is a distinct tendency for most materials and products to deviate from linearity at very high and at very low heat fluxes. Finally, it is essential to realize that the heat flux versus HRR curve rarely, if ever, passes through the origin.

This behavior is best illustrated by an example. One of the largest data sets where diverse materials were examined over a large range of heat fluxes is that which was assembled by Sorathia and co-workers at the Naval Surface Warfare Center. His data [35] are shown in Figure 2 and Figure 3. The results for the thermosetting composites clearly show an extreme variety of behaviors. More than half the materials did not ignite at the lowest heat flux used, $25 \text{ kW}\cdot\text{m}^{-2}$. Three specimens, however, did ignite and one (the Glass/Vinyl ester) burned well at that flux. The majority of the specimens showed a heat flux vs. HRR behavior which was nearly linear. Some, however, did not. Especially of interest, two showed non-monotonic behavior, with the HRR at the $100 \text{ kW}\cdot\text{m}^{-2}$ irradiance being lower than that at $75 \text{ kW}\cdot\text{m}^{-2}$. Such behavior is uncommon, but not unique.

Some old, but still indicative data were obtained in the 1970s by Parker (cited in [36]). His results for a number of fire-retardant grades of polyurethane foam are shown in Figure 4. Of the five formulations shown, three show somewhat linear behavior, whereas two clearly do not. For most categories of specimens, however, substantially more linear behavior can be seen. For instance, in a recent study of mattress composites [37], specimens were tested at two heat fluxes, 25 and $35 \text{ kW}\cdot\text{m}^{-2}$. The correlation is shown in Figure 5. A substantially linear behavior is seen, but with one salient exception: one of the tested samples is not shown on the figure, since while it ignited and burned at the $35 \text{ kW}\cdot\text{m}^{-2}$ irradiance, it did not ignite at $25 \text{ kW}\cdot\text{m}^{-2}$.

Turning to the issue of low values of irradiance, we note that ISO standard 5660 [38] cautions that test results may not be statistically significant unless the irradiance used is substantially ($10 \text{ kW}\cdot\text{m}^{-2}$) higher than the minimum irradiance level needed for sustained flaming to occur for that specimen. This has been based largely on laboratory experience, but without the benefit of much statistics for guidance. The same situation still holds true.

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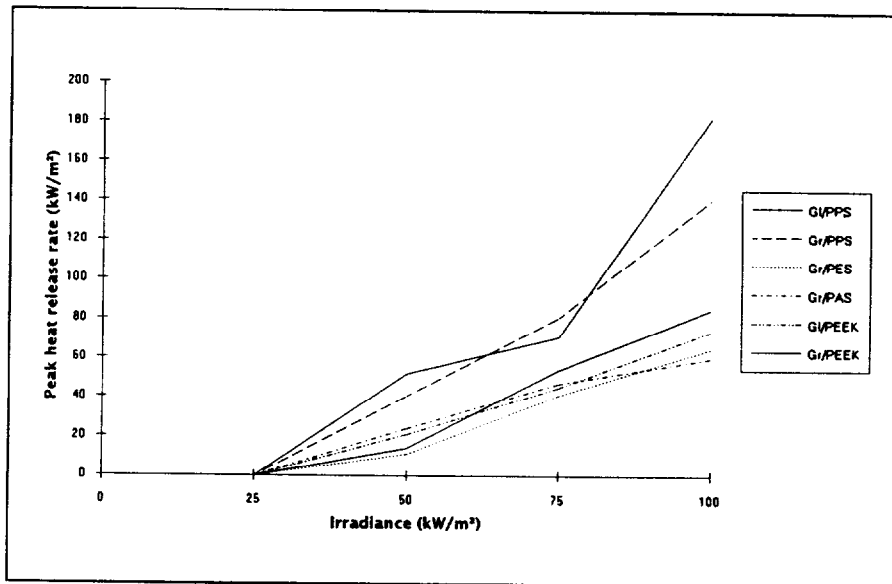


Figure 2 NSW Cone Calorimeter results for various thermoplastic composite materials

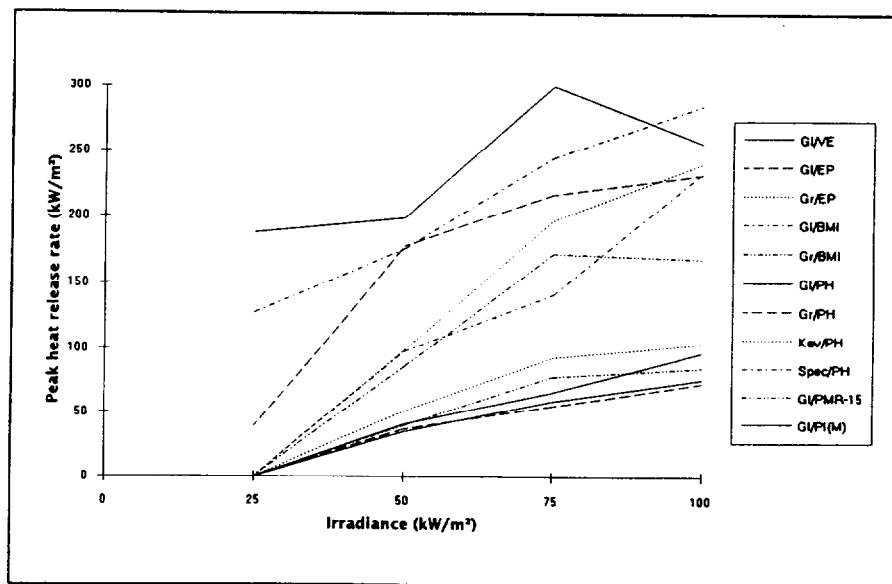


Figure 3 NSW Cone Calorimeter results for various thermosetting composite materials

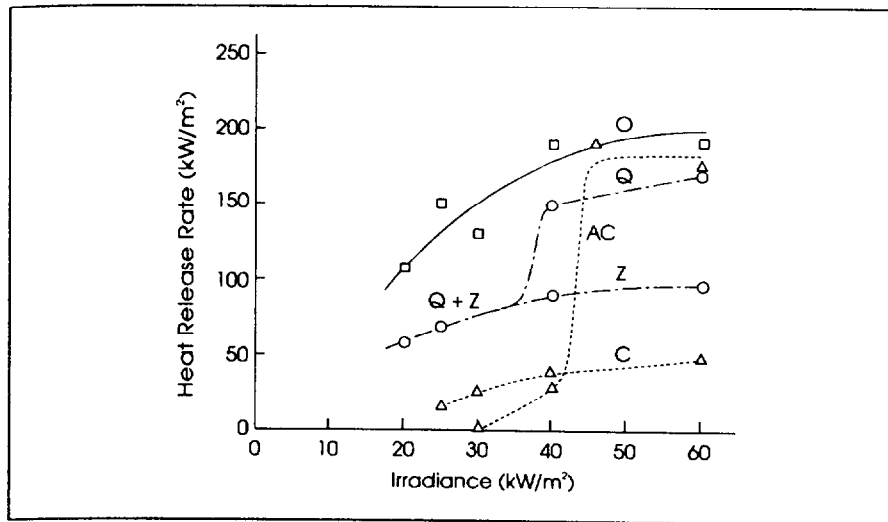


Figure 4 Results for various FR polyurethane foams, as measured by Parker in the NBS calorimeter

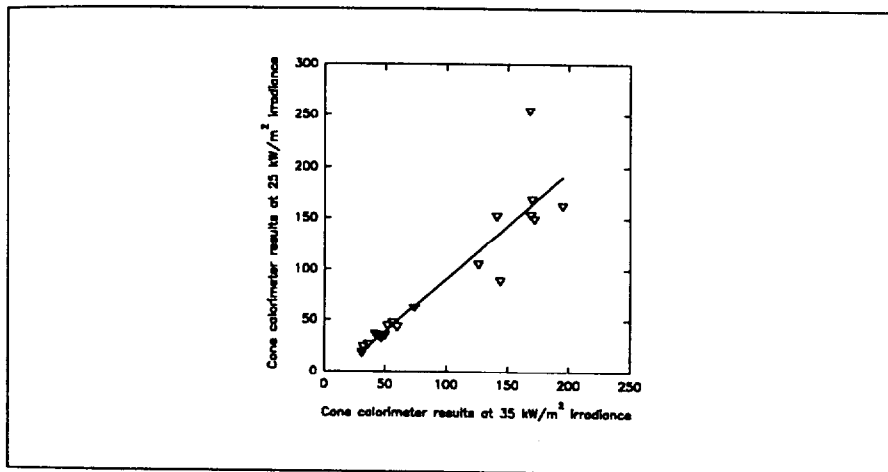


Figure 5 Correlation for HRR values (180 s averages) obtained under two different irradiances

It was mentioned above already that some mattress or upholstered furniture, especially fire-retardant ones, do not ignite at an irradiance of $25 \text{ kW}\cdot\text{m}^{-2}$. In earlier NIST testing, a similar example can be cited. A nylon/melamine-CMHR composite tested at $25 \text{ kW}\cdot\text{m}^{-2}$ showed no ignition in one test run, but with a replicate igniting in 523 s. Clearly, we cannot average the results between the runs where

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ignition occurred and those where it did not. By contrast, all of the NIST testing on upholstered furniture composites at $35 \text{ kW}\cdot\text{m}^{-2}$ produced no anomalies, indicating that it might be an appropriate irradiance for upholstered furniture testing.

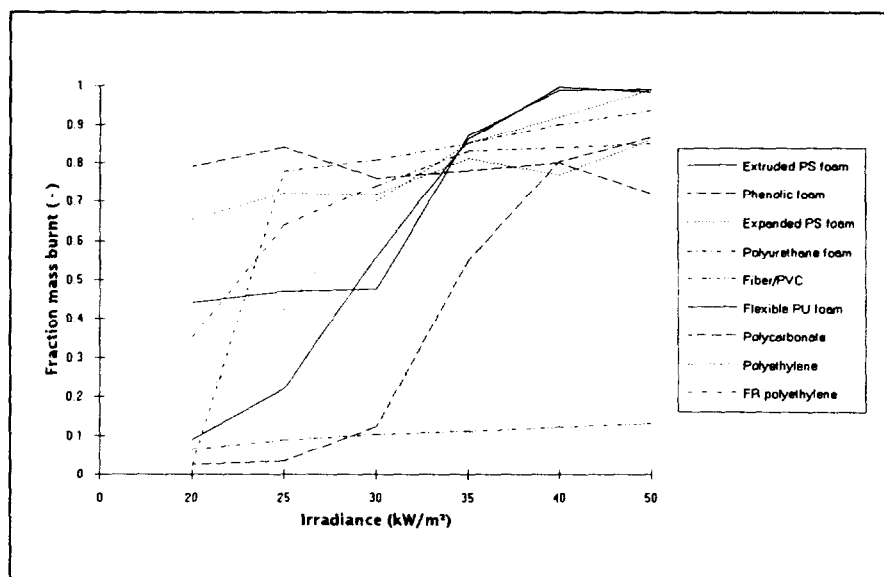


Figure 6 Mass fraction burnt, as a function of irradiance (data provided by S. Messa)

Another very important issue arising at low test irradiances is the fraction of specimen consumed. A number of materials show the following behavior. They ignite at some of the lower irradiances, but burn only very briefly; the fire goes out without the majority of the specimen being burned. The question then becomes, Is such surface-only burning realistic for the fire scenario to be considered? This, of course, cannot be answered in the general case; many fires, however, become hazardous precisely because burning is sustained and not just a surface flash. Bench-scale test data to this point have started becoming available. Messa and co-workers [39] have tested a very large number of products according to ISO technical report TR 5924 dual-chamber smoke test [40]. This method does not measure HRR; it can, however, be used to report one quantity of considerable interest—the mass fraction burned. Figure 6 shows the results for a number of diverse products tested in this way. It can be seen that for some products (e.g. the phenolic/paper) the mass fraction burned is nearly constant over the whole range of 20 to $50 \text{ kW}\cdot\text{m}^{-2}$. Other specimens (e.g. the fiber/PVC) show a gradually increasing fraction of mass burned as the irradiance is raised. Still other specimens, however, show a behavior where very little mass is lost up to even a $30 \text{ kW}\cdot\text{m}^{-2}$ irradiance, with substantial burning occurring only at higher irradiances.

The general question of minimum ignition level was explored by Scudamore *et al.* [41]. In their tests, polystyrene foam, both FR and non-FR did not ignite at $20 \text{ kW}\cdot\text{m}^{-2}$, and neither did 2 out of 3 rigid PVC formulations tested. Composites using glass reinforcement and polyethersulfone resin or polyether ether ketone resin did not ignite at either 20 or $30 \text{ kW}\cdot\text{m}^{-2}$. Other test materials ignited at $20 \text{ kW}\cdot\text{m}^{-2}$, although repeatability issues were not presented.

One type of research result which is yet unavailable is a comprehensive statistical study to demonstrate the difficulties which can be encountered when doing HRR testing too close to the critical flux for ignition. Here experience suggests that such results are likely to be highly material-dependent; thus, a wide enough range of materials would have to be explored.

STATISTICALLY-BASED SELECTION OF THE HEAT FLUX

One procedure which can be quite effective in the absence of a more physically-founded choice for test irradiance is a correlational approach. If the task requirement is not just a generalized product characterization but, rather, specific bench-scale predictions of a well-defined real-scale fire, then a suitable strategy is available. This strategy has been used less commonly than might be expected; thus, we will illustrate with an older but comprehensive example. A series of domestic upholstered furniture specimens was studied by Babrauskas and Krasny [42], wherein both large-scale furniture calorimeter data and bench-scale Cone Calorimeter data were obtained. The value of test irradiance to use was not known *a priori*. Thus, the bench-scale tests were conducted at irradiances of 25, 30, 40, and 50 kW·m⁻². Results obtained at each of these irradiances were then correlated to the peak large-scale HRR values. The goodness of fit was assessed according to the coefficient of variation, using the standard deviation obtained from least-squares fitting. The following illustrates an extract from these results, based on the 180 s average bench-scale values:

Irradiance	Coeff. of variation
25	0.051
30	0.052
40	0.059

Thus, on this basis, the flux of 25 kW·m⁻² was chosen for domestic furniture on the best correlation to the large-scale data. It is appropriate to point out here, that these old NIST tests were done prior to there being available on the marketplace the current choice of fire-improved upholstered furniture. The NFPA standard on bench-scale testing of upholstered furniture [43] specifies the use of a flux of 35, not 25 kW·m⁻². This is because the NFPA standard is addressed towards non-residential applications, and testing experience at NIST had indicated that some of the newer fire-improved materials used for these applications do not burn repeatably at the 25 kW·m⁻² irradiance, but can be tested satisfactorily at 35 kW·m⁻². We also point out that in the data listing above, the practical difference between CV = 0.051 or 0.052 or 0.059 would be very small; thus the 35 kW·m⁻² irradiance would be only trivially less optimal for residential furniture also. Similar correlational approaches for electric cables have also been described [44],[45].

FIRE MODELING NEEDS

The next step beyond correlational approaches are physics-based fire models. In general, it could be expected that heat flux specifications for fire model needs will vary widely, depending on the fire problem being represented. Currently, despite the more than 15 years of fire model development, their state of test data utilization is still rather primitive, and only a few of the models address the issue of HRR test irradiance conditions at all.

We can cite three current examples, two simple models and complex one. One simple model is the *Wickström/Göransson* model for the prediction of wall and ceiling fires [46]. In this model, the

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products. It is certainly reasonable to presume that not all the burning areas in that environment were exposed to heat fluxes quite close to $25 \text{ kW}\cdot\text{m}^{-2}$. A number of their full-scale fires reached flashover and beyond. This clearly indicated the actual presence of a wide range of heat fluxes on various portions of the walls and ceiling. Nonetheless, the excellent agreement of the predictions based only on the use of a single test irradiance implies a substantial linearity between the incident flux and the material response.

Another simple model is the one by Janssens for the prediction of wood materials' flame spread in the Steiner Tunnel [47]. His model is based on experimental measurements of the heat flux from the burner flames in the Tunnel; based on that, materials are tested at a $65 \text{ kW}\cdot\text{m}^{-2}$ irradiance. Good agreement is seen for a number of wood products tested.

A much more computationally-intensive model has been presented by Dietenberger [48]. In Dietenberger's model Cone Calorimeter data are taken at 25, 40, and $50 \text{ kW}\cdot\text{m}^{-2}$ irradiances. He then provides a normalization scheme whereby these data can be collapsed into a single curve of normalized time versus normalized HRR. The model then, at each step, de-normalizes the single HRR curve to obtain an imputed actual HRR for the instantaneous heat flux seen at a surface element. The experience with this approach is not large, however, it can have some very useful implications. If this technique is valid in other applications, the exact test irradiances chosen will not matter, so long as at least two different successful values are used.

PRODUCT PERFORMANCE CHARACTERIZATION

We finally turn to considering the point of view of the product maker. When application-specific guidance is not available, what should he do? Industry comments have often focussed on trying to ensure that the minimum possible heat flux will be used for testing, makers fearing that their product will be "overwhelmed" otherwise. Apparently, the fear is that products show large, real HRR differences at lower irradiances, but that test results collapse into some single curve at higher irradiances. This fear is not justified, however, either on the basis of physics or statistics. Physically, such a viewpoint would be justified if heat fluxes greater than those encountered in appropriate fire environments would be demanded. We have seen above, however, that peak heat fluxes less than $35 \text{ kW}\cdot\text{m}^{-2}$ are rare in real fires, and that values of $50 \text{ kW}\cdot\text{m}^{-2}$ are common in quite mild scenarios. Thus, the range of 35 to $50 \text{ kW}\cdot\text{m}^{-2}$ could be taken to represent numerous small-fire scenarios. Whether the product would perform better at lower heat fluxes is irrelevant, then, if such low values do not adequately relate to the fire environment. From the point of view of statistics, similar conclusions can be drawn. Consider, for example, the data of Figure 2 or Figure 3—it is clear that at higher irradiances the differences between products are in many cases *greater*, not *smaller*. Statistics from tests performed at irradiances very close to the minimum critical flux may, of course, show extreme product variations, but these variations are not repeatable and are not a valid reflection of actual performance.

Probably the most thoughtfully developed testing scheme for 'general' (*i.e.*, where the end-use application is not yet known) product testing is the one proposed by the researchers working on the EUREFIC program [49]. Their proposal is shown in Figure 7. It will be noted that a salient feature of this testing scheme is that the product is always tested at two heat standardized fluxes, but those two being chosen to be the lowest consistent with the actual product behavior. Such a scheme can well be recommended for manufacturers' guidance in general. It also has the advantage that data will be automatically available for models, such as Dietenberger's, where valid information at more than one heat flux is a prerequisite.

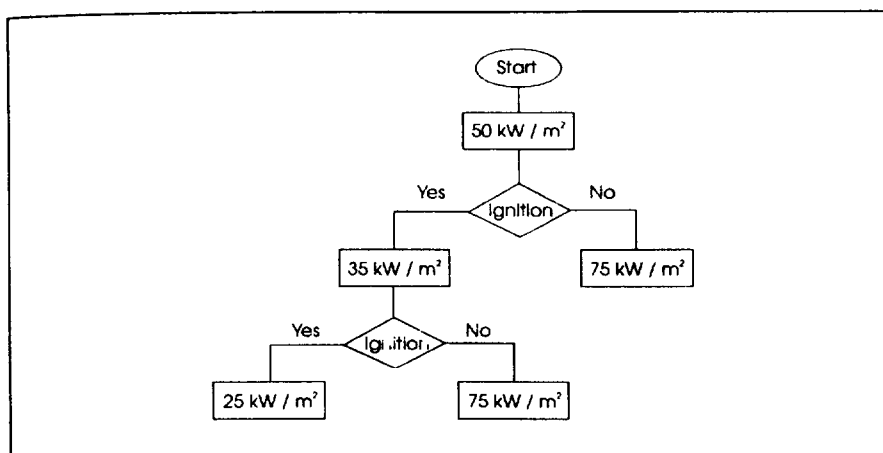


Figure 7 Testing scheme proposed in conjunction with the EUREFIC research program

ADDITIONAL ISSUES

All of the discussion above was implicitly predicated on there being a *uniform* heat flux from the bench-scale HRR apparatus heater to the specimen. The reason for this requirement stems from the needs of fire modeling. As seen above, it can be difficult to determine the proper heat flux to be used when a uniform heat flux is considered. With a non-uniform heat flux, the situation becomes exceedingly difficult to handle. Even the most advanced current-day models demand data in the form of HRR for a small surface element exposed to a uniform heat flux, although separate tests at several heat fluxes might be required. Older test apparatuses were not necessarily designed with this objective in mind. Thus, for instance, the ASTM E 906 (OSU) HRR apparatus [50] intrinsically provides a somewhat uniform heat flux to vertical specimens, but strongly non-uniform to horizontal ones [51]. What is even more troublesome, many studies with that apparatus have used an 'impinging' pilot. Such a pilot is one which does not merely ignite the gases leaving the surface, but actually impinges upon the surface and provides strong, local heating not accounted for in setting the test irradiance. Data from such tests are hard to compare to data obtained under uniform heat flux conditions; when a comparison is attempted, it will typically be seen that the 'effective' heat flux from the apparatus having the localized hot spot is higher than indicated by the imposed radiant flux level [52].

With regard to correlational approaches for predicting full-scale HRR, the discussion until now presumed that a *single* irradiance would be used for the bench-scale tests in the actual correlation, although more than one test series might initially have to be run. This assumption does not necessarily have to be made—one can explore correlations which simultaneously use data from test series at several different irradiances. To date, only the work of Hirschler [53] has explored such an approach. Whether in the general case there arises a need for such refinement still remains to be seen. It might be pointed out, however, that if a single-best flux is sometimes difficult to determine, determining the two best ones may be no easier.

CONCLUSIONS

Despite the number of years during which HRR testing has been actively pursued, definitive recommendations for the choice of test irradiance cannot yet be given. This notwithstanding, some useful, practical advice is possible. The main points are:

- Even very small fire sources typically show peak heat fluxes in the vicinity of $35 \text{ kW}\cdot\text{m}^{-2}$ and almost never below $25 \text{ kW}\cdot\text{m}^{-2}$.
- For many fire scenarios, bar those involving post-flashover fires, a test irradiance of $35 \text{ kW}\cdot\text{m}^{-2}$ is often found to be suitable. Considerably more product performance information can be obtained, however, by adopting the scheme proposed during the EUREFIC research program, where it is ensured that data at two separate irradiances are available.
- Very little guidance is yet available for those cases where a room fire has not reached flashover, yet heat flux contributions from the hot upper gas layer have become significant.
- Irradiances in the vicinity of $50 \text{ kW}\cdot\text{m}^{-2}$ can be appropriate for testing products for facade usage.
- Military applications specify the use of irradiances as high as $100 \text{ kW}\cdot\text{m}^{-2}$, however, full-scale validation data are still sparse for these applications.
- Correlational approaches can be successful in identifying the correct bench-scale test conditions, including irradiance, when more detailed fire modeling information is unavailable.
- For many materials and products, the HRR problem exhibits substantial linearity over the range of intermediate heat fluxes. That is, provided that neither heat fluxes too close to the critical irradiance nor exceedingly high ones are considered, the exact choice of test irradiance may have only a modest effect on product rankings and on full-scale performance prediction.
- HRR information is, as yet, rarely sought for post-flashover fires. Nonetheless, such fires will often involve heat fluxes well beyond the $100 \text{ kW}\cdot\text{m}^{-2}$ that is the upper limit of test irradiances possible with today's bench-scale HRR equipment. It may be possible, however, to use test results obtained at lower irradiances to the extent that linearity can be relied upon.
- Room fire models currently available are very primitive in terms of their HRR data treatment. As these models are refined, it can be expected that focused guidance will become available on test irradiances that are most appropriate for modeling usage.
- Further work still needs to be done on numerical characterization of the repeatability variations that are seen as the critical irradiance is approached.

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